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Fifth Quarterly Progress Report

on

THE TRANSFORMATION OF AUSTENITE UNDER EXTERNALLY APPLIED TENSILE STRESS

For the Period March 1, 1953 to May 30, 1953

by

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Fifth Quarterly Progress Report

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THE TRANSFORMATION OF AUSTENITE UNDER EXTERNALLY APPLIED TENSILE STRESS

This report constitutes a summary of work performed during the last quarter period (March 1, 1953 to May 30, 1953) on the transformation of austenite to upper bainite in AISI 1085 and 4340 steels. Preliminary data are also presented on some mechanical properties of lower bainite resulting from stress application during isothermal transformation.

Preparation of the specimens, experimental procedure, and calculation of stress, strain, strain energy and rate of transformation are similar to those reported previously.(1) (2)

AISI 1085 - UPPER BAINITE STUDIES

Experimental Results

A complete series of experiments were carried out on AISI 1085 steel at the high temperature bainite transformation temperature level of 700°F. A few preliminary experiments were conducted at a transformation temperature of 845°F, but it was found that the beginning time of transformation was so short that the specimen started to transform before reaching the transformation bath temperature, even in the absence of applied stress.

Table I gives the range of stresses applied, isothermal holding time and other relevant informations regarding the transformation of AISI 1085 steel at 700°F.

The amount of bainite formed due to isothermal transformation is plotted vs. log-time under different average stress conditions and is

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(1) Third Quarterly Progress Report, February 17, 1953, p. 1.

(2) Fourth Quarterly Progress Report, April 30, 1953, pp. 1-3, 6-7.

shown in Fig. 1. The effect of applied stress on the beginning and ending* times of transformation is shown in Table II.

From Fig. 1, one can obtain a relationship between the applied stress and percent bainite formed for selected periods of isothermal transformation at the transformation temperature level. The data thus obtained are plotted in Fig. 2. In Fig. 3 is plotted the variation of true strain with time under different average true stresses. The amount of bainite formed due to isothermal holding for constant periods of time vs. true strain is shown in Fig. 4.

True stress-strain curve for unstable austenite prior to the appearance of any isothermal decomposition product is plotted in Fig. 5. This curve is plotted from the true strain-time relationship data shown in Fig. 3, for such short periods of time during which even under the largest applied stress no isothermal transformation occurred. The true stress-strain relationship for longer periods of holding at the isothermal transformation temperature is shown in Fig. 6. These curves are also similarly obtained from the plotted data of Fig. 3. Applied strain energy values are obtained by measuring the area under the curves in Fig. 6 and these values are converted to cal. per mole quantities through conversion factor reported previously.(3) The amount of bainite formed due to isothermal holding for constant periods of time vs. applied strain energy is shown in Fig. 7.

Some experiments were conducted with AISI 1035 steel specimens which were kept under stressed condition for a part of the total time of isothermal transformation. In Table III is given the results of the experiments in which the specimens being initially allowed to transform under applied

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* The criteria of the beginning and end of transformation are taken, respectively, at 1% and 99% bainite formation.

(3) Fourth Quarterly Progress Report, April 30, 1953, p. 3.

stress were subsequently allowed to transform with the stress removed. These data are shown in Fig. 8.

Table IV shows the results obtained when specimens were initially allowed to transform without applied stress, stress being subsequently applied. These data are shown in Figs. 9, 10, and 11.

From the data of Table IV, Fig. 12 is plotted to illustrate the dependence of true strain on the amount of bainite present prior to the application of stress. This curve shows the variation of the strength of the austenite-bainite mixture at the transformation temperature level in relation to the amount of bainite present, under the assumption that the true strain under stress indicates the strength characteristic of the structure.

In Fig. 13 is plotted the $\log_e(1-x)$ vs. time (t) under different average stresses, where x is the fractional amount of bainite formed in time t. From a few experimental data an approximate curve is also shown for an applied stress of about 100,000 p.s.i.

AISI 1085 STEEL - LOWER BAINITE PROPERTIES

Two experimental runs were made in the low temperature bainite transformation temperature level at 535°F. One specimen was allowed to transform to > 99% bainite under no applied stress and another to approximately the same amount under a stress of about 60,000 p.s.i. These two specimens were then tested in a pendulum type wire testing machine. The data indicate that the true breaking stress for both the specimens is about 360,000 p.s.i. The Youngs Modulus for both the specimens is about 30×10^6 p.s.i., but the true stresses corresponding to 0.002 in/in true strain are 270,000 p.s.i. and 320,000 p.s.i. for the bainite products formed without stress and with stress, respectively. Although the two stress values are not too precise, they nevertheless indicate that the bainitic product formed under stress

has a higher yield strength or a higher 0.2% offset stress than that formed under no stress. The elongation in 2 inches of the bainitic product formed under stress is slightly lower than that of the product formed under no stress.

Hardness measurements on bainite formed at 535°F under no stress and under different magnitudes of applied stresses are observed to be virtually the same. An average DPH of 650 is obtained (500 g. load), corresponding to a converted R"c" 57.3.

Discussion of the Results:

It is quite evident from Fig. 1 that under increasing amount of stress both the beginning and ending times of transformation are shortened and these results are given in Table II. It is also observed that a very high stress of the order of 100,000 p.s.i. causes the beginning and the ending of transformation times to reduce by factors of 9 and 4, respectively.

It can also be observed from Fig. 1 that the effect of stress on the amount of bainite formed is significantly changed at a certain applied stress level. This is also clearly evident in Fig. 2, which indicates that when the applied stress level falls in the range of 26,000 to 29,000 p.s.i. (henceforth to be referred to as the critical stress range), the amount of bainite formed is very much increased for those periods of times for which transformation under no stress lies in the range of 1% to 20%. The effect of stress of an amount lower or higher than this is approximately linear for the same periods of time.

From Fig. 5, the yield stress of the unstable austenite is indicated to be 26,000 p.s.i. It is quite evident that this yield stress is closely related to the critical stress mentioned above.

Fig. 4 shows the variation of the amount of bainite transformed with true-strain for different periods of holding time and the relationship

is similar to that shown in Fig. 2. It is indicated from Fig. 4 that the amount of bainite formed increases to a large extent when the true strain value lies in the range of 0.028 to 0.032 in/in (henceforth to be referred to as critical true strain). From the data of Fig. 6, the stress levels corresponding to these ranges of critical true strains is observed to be 24,000-27,000 p.s.i. These stress levels correspond well to the critical stress range of 26,000-29,000 p.s.i. and the yield stress of 26,000 p.s.i.

Applied strain energy values (obtained graphically from Fig. 6) vs. amount of bainite formed are plotted in Fig. 7. It is quite evident that a critical strain energy is involved in promoting the amount of bainite formed. This is what is expected from the critical stress and critical strain values obtained from the other figures.

The data plotted in Fig. 8 shown in the form of various letter symbols and identified in Table III, indicate that when the austenite is initially stressed with a stress above the range of critical stresses for a length of time, and the externally applied stress is subsequently withdrawn, the transformation characteristic of the remaining austenite after the withdrawal of the applied stress, follows closely that of the austenite under applied stress. This indicates that the highly deformed regions in the austenite grains, behaving as nucleating centres, are not sufficiently relaxed to allow the transformation to proceed at a rate corresponding to that under no stress. This can be seen in Fig. 13, where the slope of the curve at any instance gives the rate of decomposition of the residual austenite.

It can be observed from Fig. 13 that the rate of decompostion of residual austenite $\left\{\frac{1}{1-x}\frac{dx}{dt}\right\}$ increases up to a certain value and then becomes fairly constant. This constant rate of decomposition is found

to vary with applied stress and these data are shown in Table V. These data indicate that below the critical range of stresses and even a little above it, the effect of stress in increasing the constant maximum rate of decomposition of residual austenite is not pronounced. It is also evidenced from Fig. 13 that with increasing amounts of applied stresses the slope of the curve is reaching a constant value at an earlier stage of the decomposition of austenite. For example, at stresses up to 33,000 p.s.i. (which is somewhat above the critical stress range) the maximum in the slope is reached when about 53% of austenite has been transformed to bainite, whereas, in the cases of 46,000 p.s.i., 60,000 p.s.i., and 100,000 p.s.i. stresses the respective constant rates are reached after about 46%, 41%, and 30% (approximate) of austenite have decomposed.

The data plotted in Fig. 9, shown in the form of various letter symbols and identified in Table IV, indicate that when the initial transformation is of the order of 20% or more, the subsequently applied stress of about 60,000 p.s.i. does not cause any appreciable change in the transformation characteristic of the remaining austenite. This is to be expected because owing to an initial transformation of 20% or more, the strength of the aggregate increases to such an extent that a stress of 60,000 p.s.i. subsequently applied is not sufficient to accelerate the transformation to any appreciable extent.

The data plotted in Figs. 10, and 11 shown in the form of various letter symbols identified in Table IV show that the effect of a stress greater than the critical stress applied for a period of time sufficient to produce a strain larger than the critical strain, is most marked when the stress is applied at the end of the incubation period under no stress, compared to application of stress before or after this time.

The variation of the strength of the austenite-bainite mixture with the amount of bainite present, as reflected in the true strain values, is shown in Fig. 12. The straight-line portion of the curve indicates

that the strength of this aggregate is a logarithmic function of the amount of bainite present in the austenite-bainite mixture and is not a linear function, as might be expected from ordinary laws of mixtures.

Metallographic examination of the microstructures of the specimens reveal many interesting aspects of transformation. The effect of stress in increasing the amount of bainite formed is shown in the series of photomicrographs of Fig. 14. The effect of stress higher than critical stress in decreasing the size and producing preferrential distribution of bainitic products is not very marked. In Fig. 15 is shown preferrential distribution of bainitic products at a stress of 60,000 p.s.i. and twining of the prior austenite (now martensite) due to a stress of 100,000 p.s.i. As illustrated in Fig. 16, bainite formed under high stresses is preferrentially formed at grain boundaries, and in some cases completely outlining the prior austenite grain.

Summary and Conclusions:

An applied stress exceeding the yield stress of the austenite was found to increase the amount of transformation to a large extent. It was also observed that this large increment in transformation is related in the same manner to a critical true strain and deformation energy value. Thus it is observed that the effect of applied stress on high temperature bainite transformation is almost identical to that on low temperature bainite transformation, reported previously.[4]

One of the current theories of bainite formation suggests that supersaturated ferrite forms from unstable austenite, and owing to diffusion of carbon within the ferrite plates, iron carbide particles

(4) Fourth Quarterly Progress Report, April 30, 1953, pp. 9-10.

are eventually precipitated. It is suggested by the experimental results presented as related to stress application during and prior to transformation, that the body centered cubic structure of ferrite be formed by slip occurring within the face centered cubic lattice of austenite, and thus be a mechanism for the formation of supersaturated ferrite platelets. The observed effects of stress on the beginning and ending times of transformation, the rate of decomposition of residual austenite, the earlier attainment of the constant rate of decomposition of residual austenite and the effects observed in Figs. 8, 9, 10, and 11 can be quite adequately explained from this theory and the proposed mechanism of supersaturated ferrite formation. The not so pronounced effect of increasing stress above the critical stress on the fineness and preferrential distribution of the high temperature bainite, as contrasted to that on low temperature bainite, may probably be due to the higher rate of diffusion of carbon at the high temperature transformation level.

The other theory of bainite formation by nucleation and growth suggests the controlling factor to be the diffusion rate of carbon in austenite. This theory alone can not adequately explain the observed effects.

AISI 4340 STEEL - UPPER BAINITE STUDIES

Published isothermal diagrams of AISI 4340 steel show that the transformation of austenite to upper bainite, in the temperature range of 800° - 1000°F, is completed only after an extremely long sojourn at temperature. Furthermore, the onset of transformation at about 850°F occurs in approximately 15 sec., whereas at 1000°F the transformation starts after an elapsed time of about 30,000 sec. This part of the report summarizes the transformation studies carried out at a temperature of 845°F under no

applied stress and under an applied stress of 60,000 p.s.i. This rather large stress was selected because it was believed that a large acceleration in transformation rate would be required to bring the time of complete transformation within reasonable limits.

The transformation data are shown in Fig. 17.

Discussion of Results:

It is observed in Fig. 17 that the beginning times of transformation under no stress and 60,000 p.s.i. are about 20 and 5 sec., respectively. Thus, the beginning time of transformation is reduced by a factor of 4 under an applied stress of 60,000 p.s.i. It may be noted in Fig. 17 that as transformation proceeds this factor increases very rapidly, and this circumstance is summarized in Table VI.

It is of interest to note that the time required under no stress to secure 99% bainite, compared to the time required under 60,000 p.s.i., is greater by a factor of about 10,000. This value is based upon a roughly extrapolated time (Fig. 17) of 10^9 to 10^{10} sec. for the formation of 99% bainite under no stress. From a plot of $\log_e (1-x)$ vs. time, calculations have been made which show that the maximum rates of transformation of residual austenite $\left\{-\frac{1}{1-x} \cdot \frac{dx}{dt}\right\}$, both under no stress and an applied stress of 60,000 p.s.i. are 0.14% bainite/sec. and 3.0% bainite/sec., respectively. Thus the effect of this stress is found to increase the maximum rate of transformation by a factor of about 20 whereas the effect of the same amount of stress at a lower bainite transformation temperature level of 650°F, reported previously, [5] is about 4.6.

As illustrated in Fig. 18, the bainitic structures formed under 60,000

(5) Fourth Quarterly Progress Report, April 30, 1953, p. 16.

p.s.i. and no stress show no appreciable difference at a magnification of 1500, particularly in randomness of distribution and fineness of the carbide particles.

Summary and Conclusions:

A stress of 60,000 p.s.i. is found to effect the rate of transformation in such a way as to decrease the ending time of transformation by a factor greater than 10,000. The mechanism of bainite transformation under stress, suggested earlier in this report, explains this effect adequately. Owing to the high temperature of transformation the amount of deformation suffered by the specimen is large (25% elongation in about 5 inches) and as a consequence of the attendant strain energy the transformation proceeds at a high rate within a few seconds subsequent to the onset of transformation. Although the applied stress brings about virtual ending of transformation in about 100,000 sec., the sluggishness of transformation near the end of the process is evident from the circumstance that about 80% of bainite is formed within 35 sec.

Although no difference was observed microscopically in the size and shape of the carbide particles in the bainite formed under no stress and 60,000 p.s.i., electron diffraction and microscopic studies will be made of selected structures.

George L. Kehl

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Project Director

Table I - Range of Transformation Times and Applied Stresses Relative to AISI 1085 Steel.

Austenitizing Treatment		Isothermal Salt Bath Temperature °F	Range of Isothermal Transformation Times, Sec.	Range of Applied Stress p.s.i.	Austenitic Grain Size at 1620°F A.S.T.M.
Temperature °F	Time Min.				
1620	7	700	5-150	0-100,000	5-6

Table II - Effect of Applied Stresses on the Beginning and Ending Times of Isothermal Bainite Formation at 700°F, AISI 1085 Steel.

Applied Stress, p.s.i.	Ratio of $\frac{\text{Time to form 1\% bainite under no stress}}{\text{Time to form 1\% bainite under applied stress}}$	Ratio of $\frac{\text{Time to form 99\% bainite under no stress}}{\text{Time to form 99\% bainite under applied stress}}$
60,000	4	2.5
100,000	9 (approx.)	4 (approx.)

Table III - The Influence on Bainite Formation at 700°F (AISI 1085 Steel) Arising from Stress Application for Different Times Prior to Transformation Under No Stress.

Transformation Schedule		Amount of bainite initially formed under 60,000 p.s.i., %	Total transformation, %	Letter symbols in Fig. 8
Time under 60,000 p.s.i., sec.	Subsequent time under no stress, sec.			
5	15	0	7	A
10	15	1	27	B
15	15	7	50	C
20	15	15	66	D

Table IV - The Influence on Bainite Formation at 700°F (AISI 1085 Steel) Arising from Different Isothermal Holding Times Under No Stress Prior to Application of Stress for Various Times.

Transformation Schedule		Amount of bainite initially formed under no stress, %	Total transformation %	Letter symbols in Figs. 9, 10 and 11	True strain in/in x 10^2
Time under no stress, sec.	Subsequent time under 60,000 p.s.i., sec.				
90	30	88	>99	K	1.7
80	30	70	98.3	J	2.4
70	30	30	97.8	I	3.2
60	30	17	92.8	H	4.5
50	30	7	82.0	G	6.5
30	30	0	80.0	F	11.4
15	30	0	61.0	E	12.5
15	15	0	9.0	M	10.8
28	17	0	17.7	N	9.7
35	15	0.5	35.4	O	7.1
45	15	3.5	40.0	P	6.7
50	15	7	42.0	Q	6.6

Table V- Variation in the Constant Rate of Decomposition of Residual Austenite at 700°F With Applied Stress. AISI 1085 Steel.

Applied Stress p.s.i.	Ratio of $\frac{\text{Constant rate of residual austenite decomposition under applied stress}}{\text{Constant rate of residual austenite decomposition under no stress}}$
10,500	1.0
21,000	1.0
33,000	1.0
46,000	1.3
60,000	2.0
100,000	$\sim$3.0

Table VI - The Effect of An Applied Stress of 60,000 p.s.i. Compared to No Stress on the Time Required to Form Different Amounts of Bainite at A Temperature of 845°F. AISI 4340 Steel.

Percentage of bainite formed	Factor by which the time of transformation is decreased by 60,000 p.s.i. stress to form the indicated amounts of bainite
1	4
25	15
50	30
75	3,500
99	10,000-100,000 **

** Owing to uncertainties in exptrapolation of the no stress curve (Fig. 17) to the time for completion of transformation, these data are shown as a range of time factors.

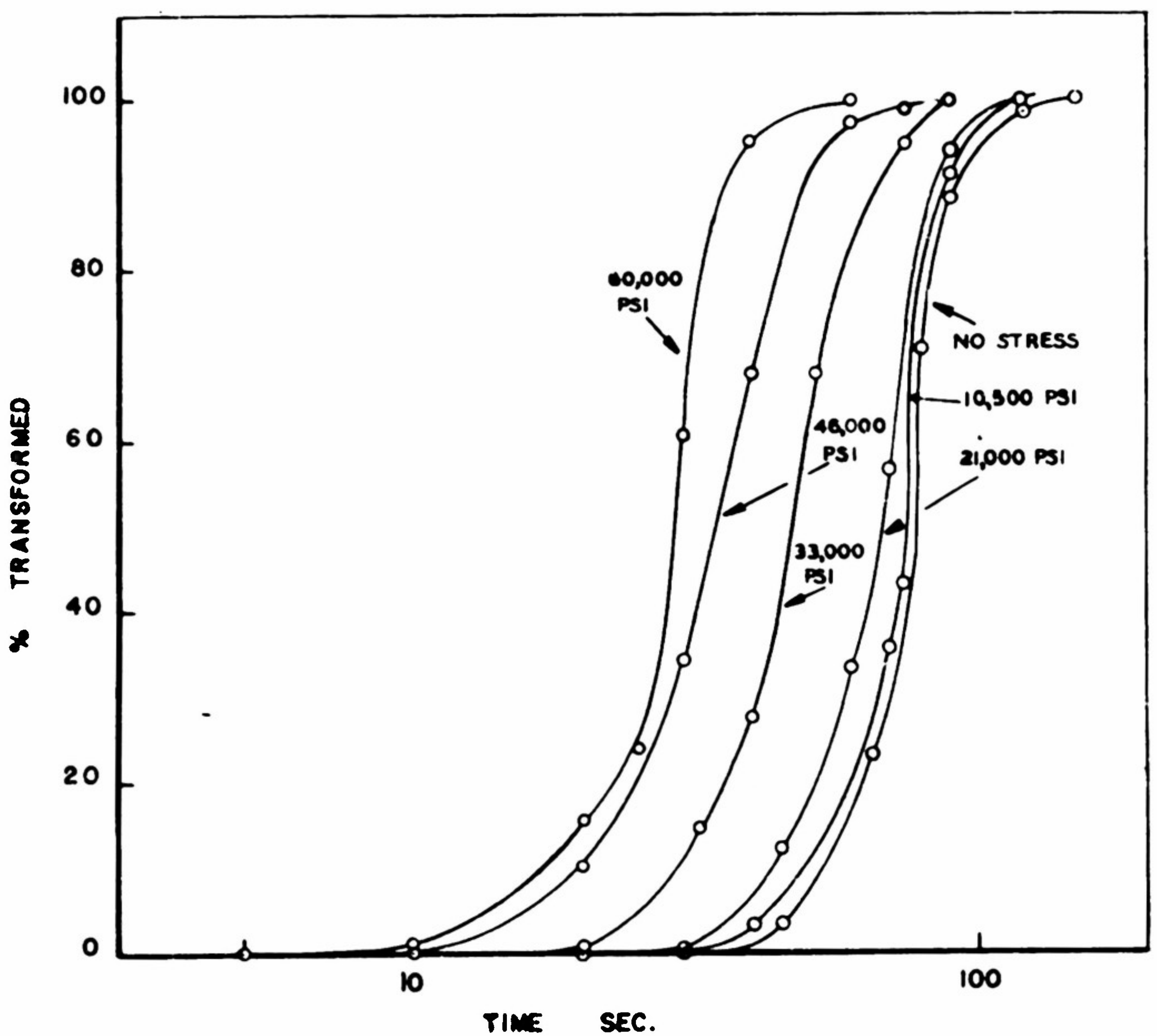


FIG. 1 AISI 1085 STEEL, ISOTHERMALLY TRANSFORMED AT 700°F

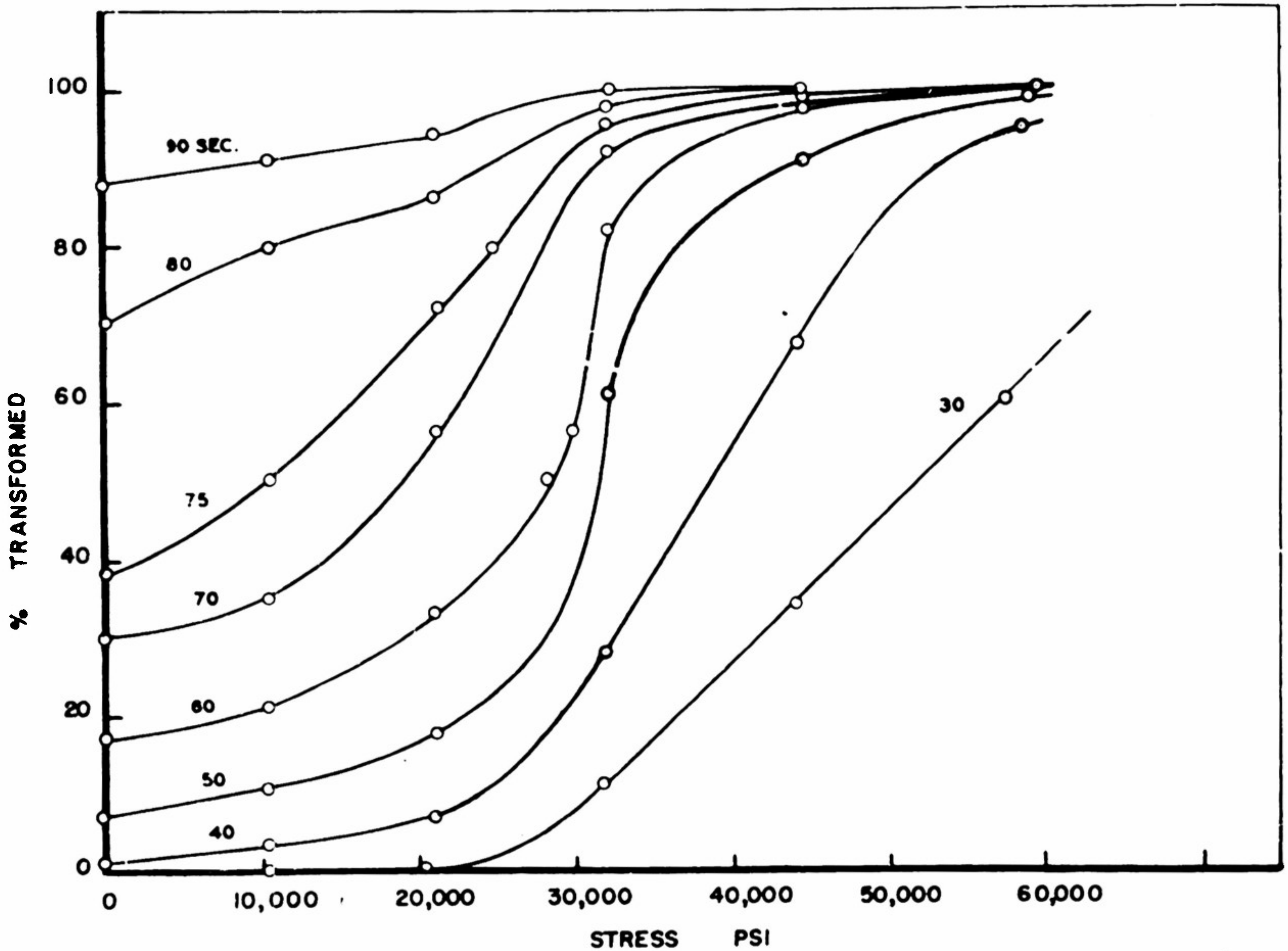


FIG. 2 AISI 1085 STEEL, ISOTHERMALLY TRANSFORMED AT 700° F

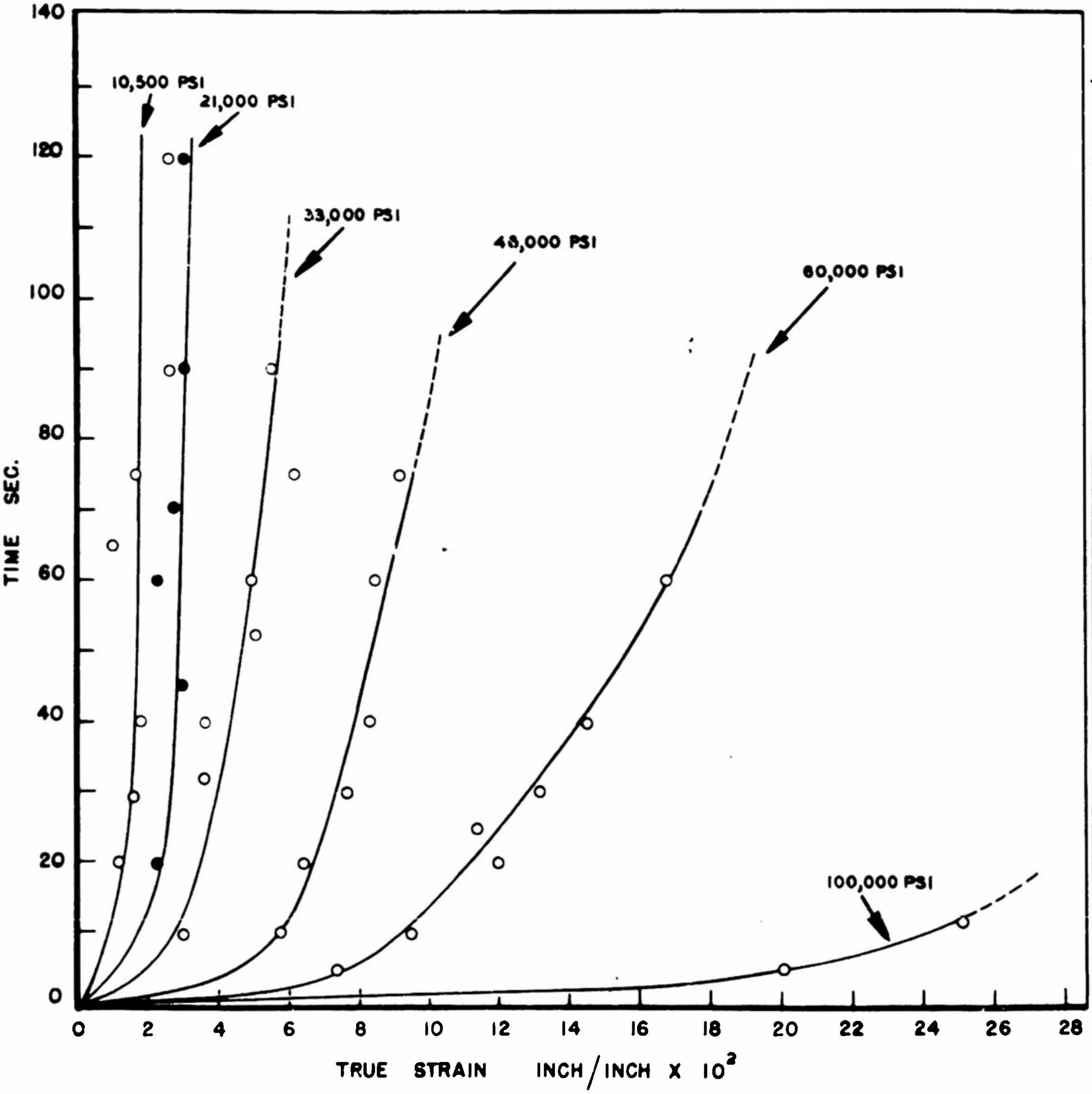


FIG. 3 AISI 1085 STEEL, ISOTHERMALLY TRANSFORMED AT 700° F

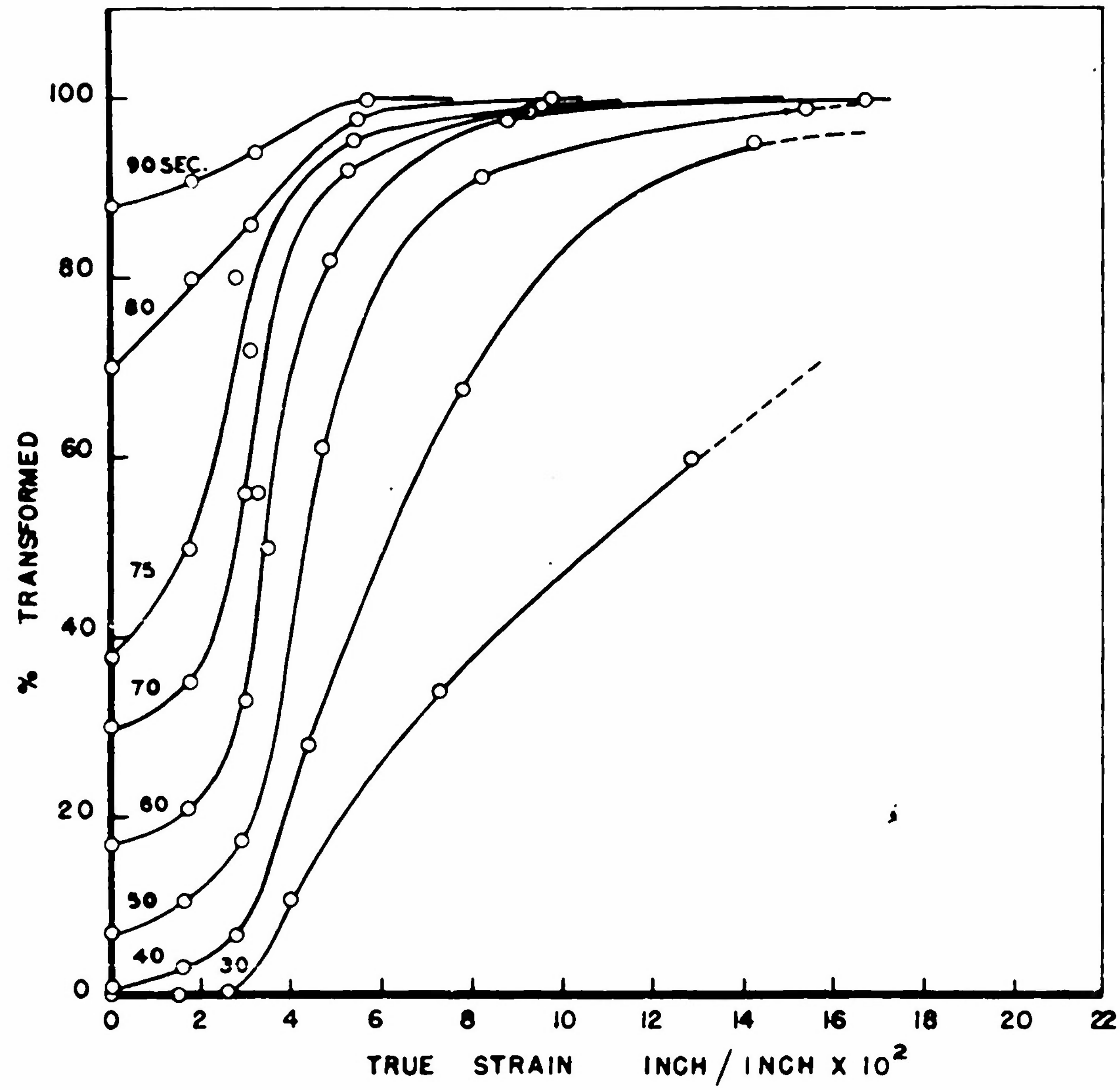


FIG. 4 AISI 1085 STEEL, ISOTHERMALLY TRANSFORMED AT 700° F

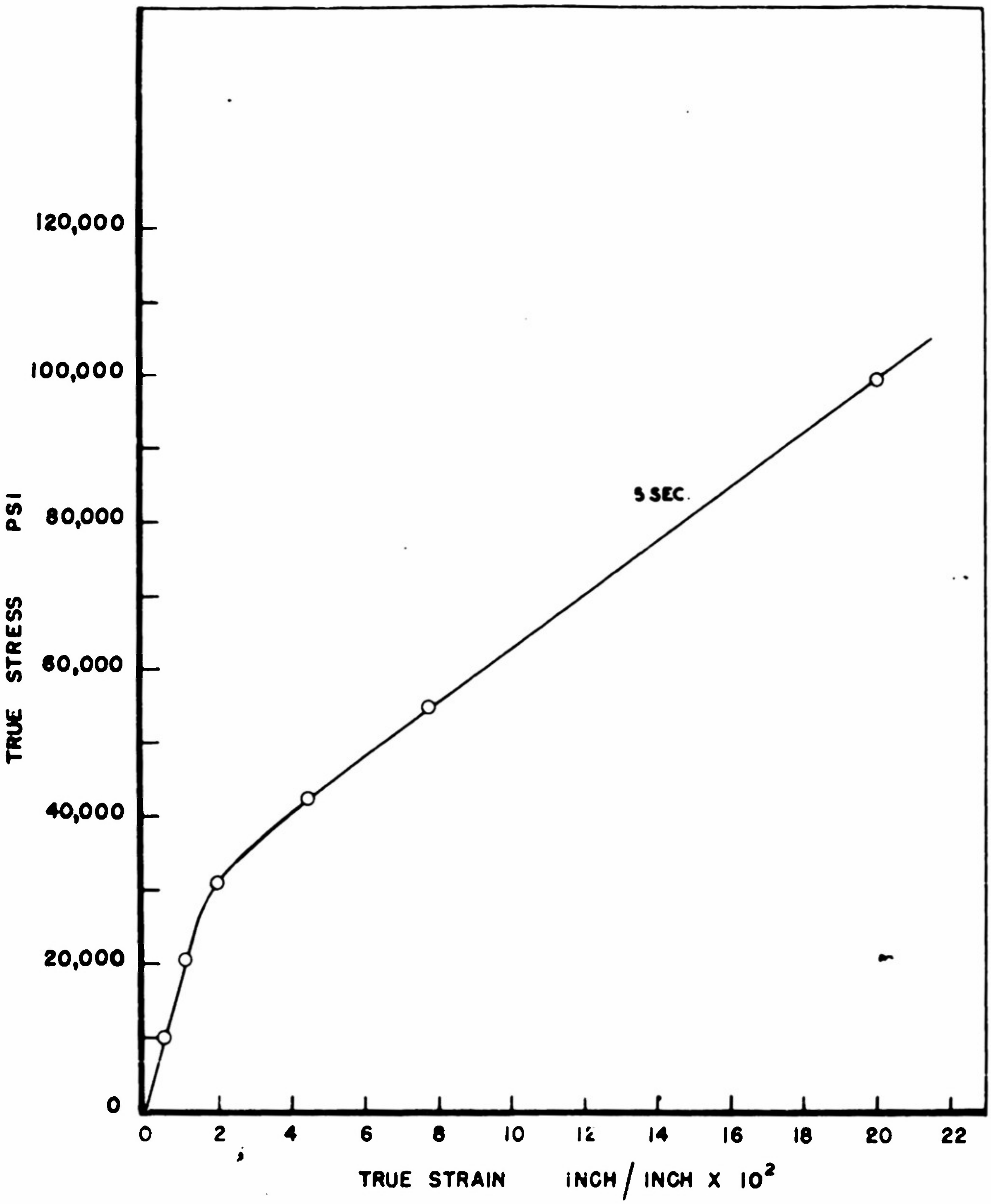


FIG. 5 TRUE STRESS — STRAIN RELATIONSHIP FOR AISI 1085 UNSTABLE AUSTENITE AT 700°F PRIOR TO ISOTHERMAL TRANSFORMATION

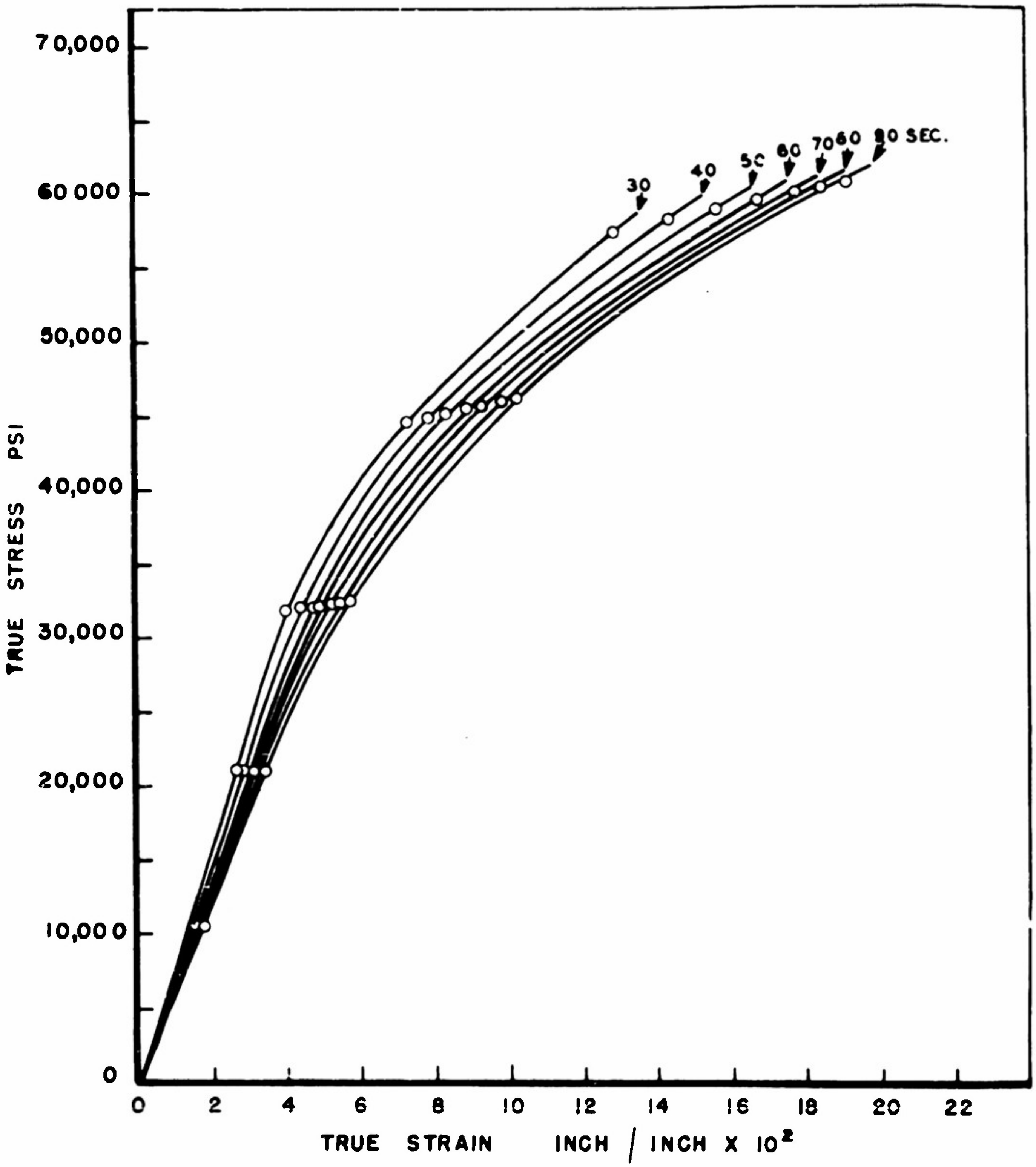


FIG. 6 TRUE STRESS STRAIN RELATIONSHIP OF AISI 1085 UNSTABLE AUSTENITE AT 700°F PRIOR TO AND INCLUDING ISOTHERMAL TRANSFORMATION AS A FUNCTION OF THE DURATION OF ISOTHERMAL HOLDING AT THE TRANSFORMATION TEMPERATURE LEVEL

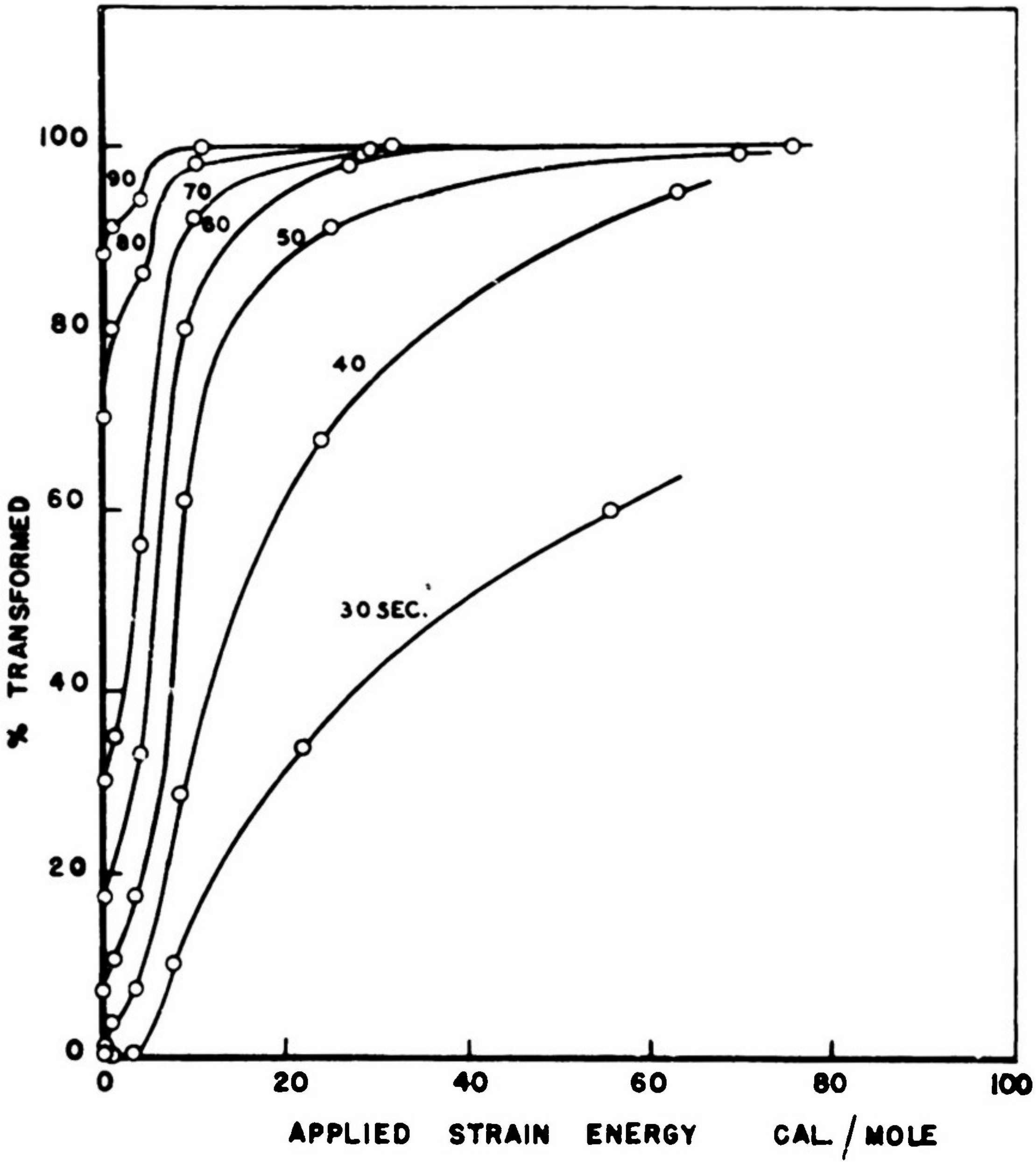


FIG. 7 % TRANSFORMED — STRAIN ENERGY RELATIONSHIP OF AISI 1085 STEEL, ISOTHERMALLY TRANSFORMED AT 700°F FOR DIFFERENT CONSTANT PERIODS OF TIME

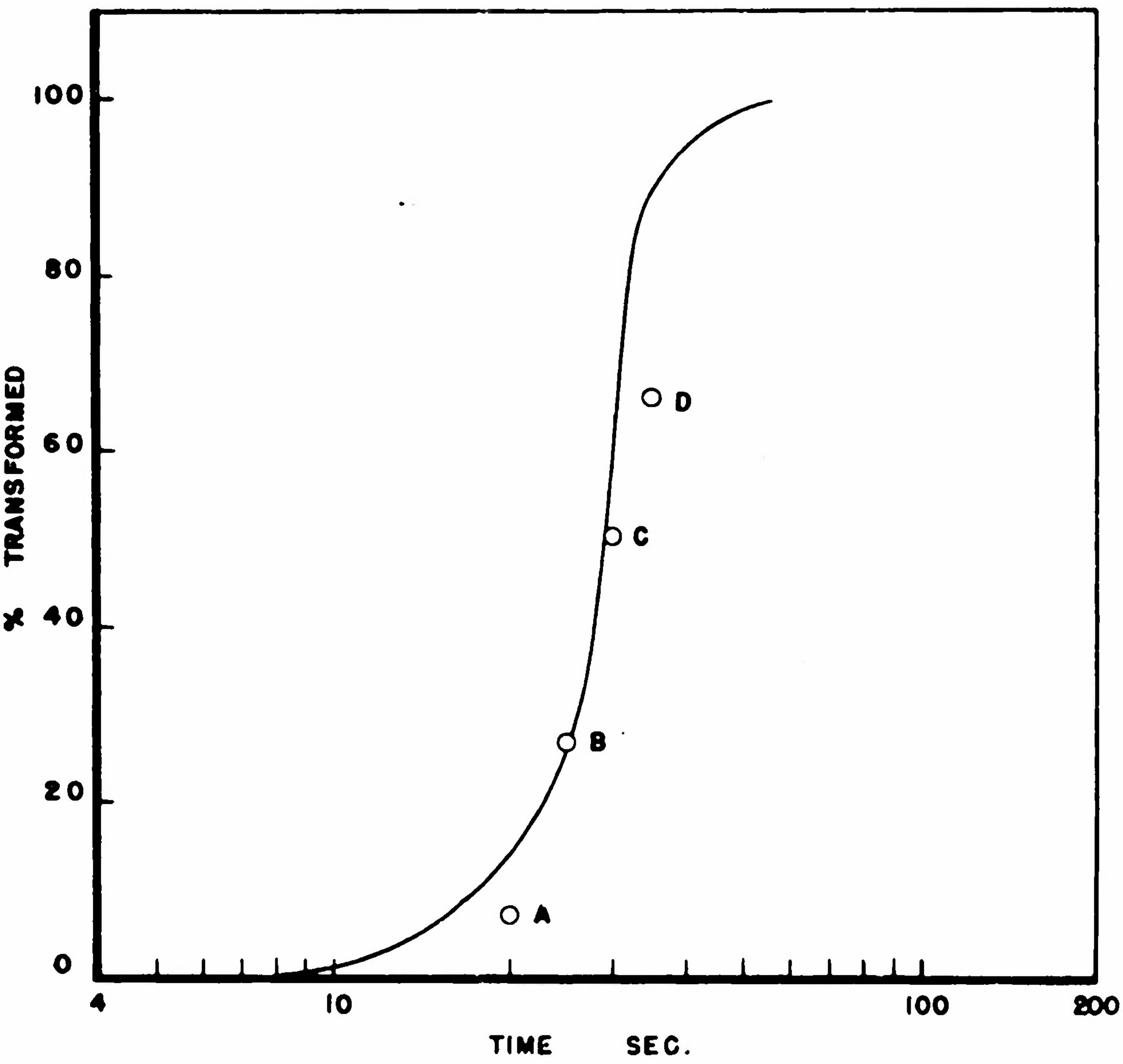


FIG. 8 AISI 1085 STEEL, ISOTHERMALLY TRANSFORMED AT 700° F UNDER AN APPLIED STRESS OF 60,000 PSI

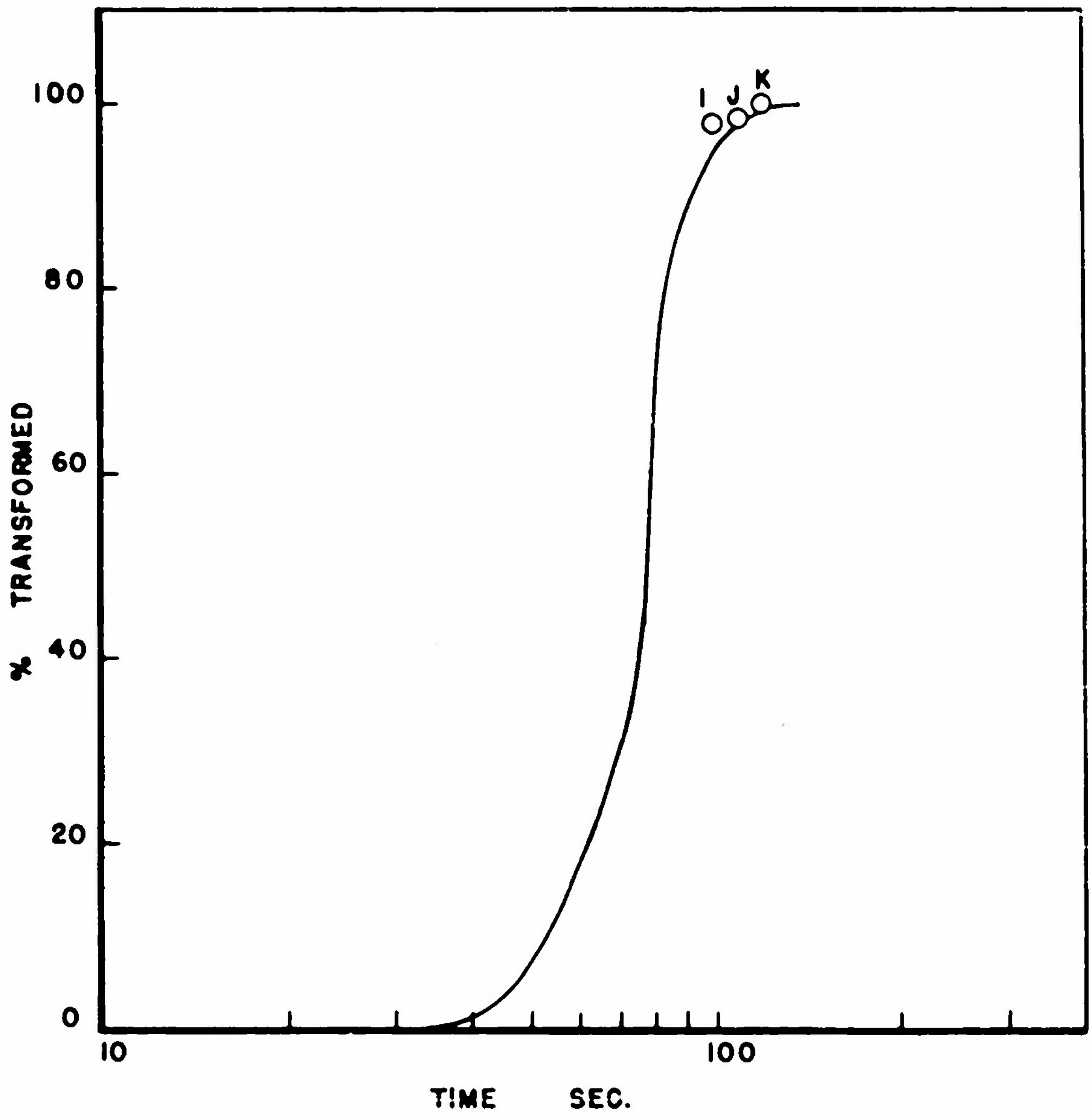


FIG. 9 AISI 1085 STEEL, ISOTHERMALLY TRANSFORMED AT 700° F UNDER NO APPLIED STRESS

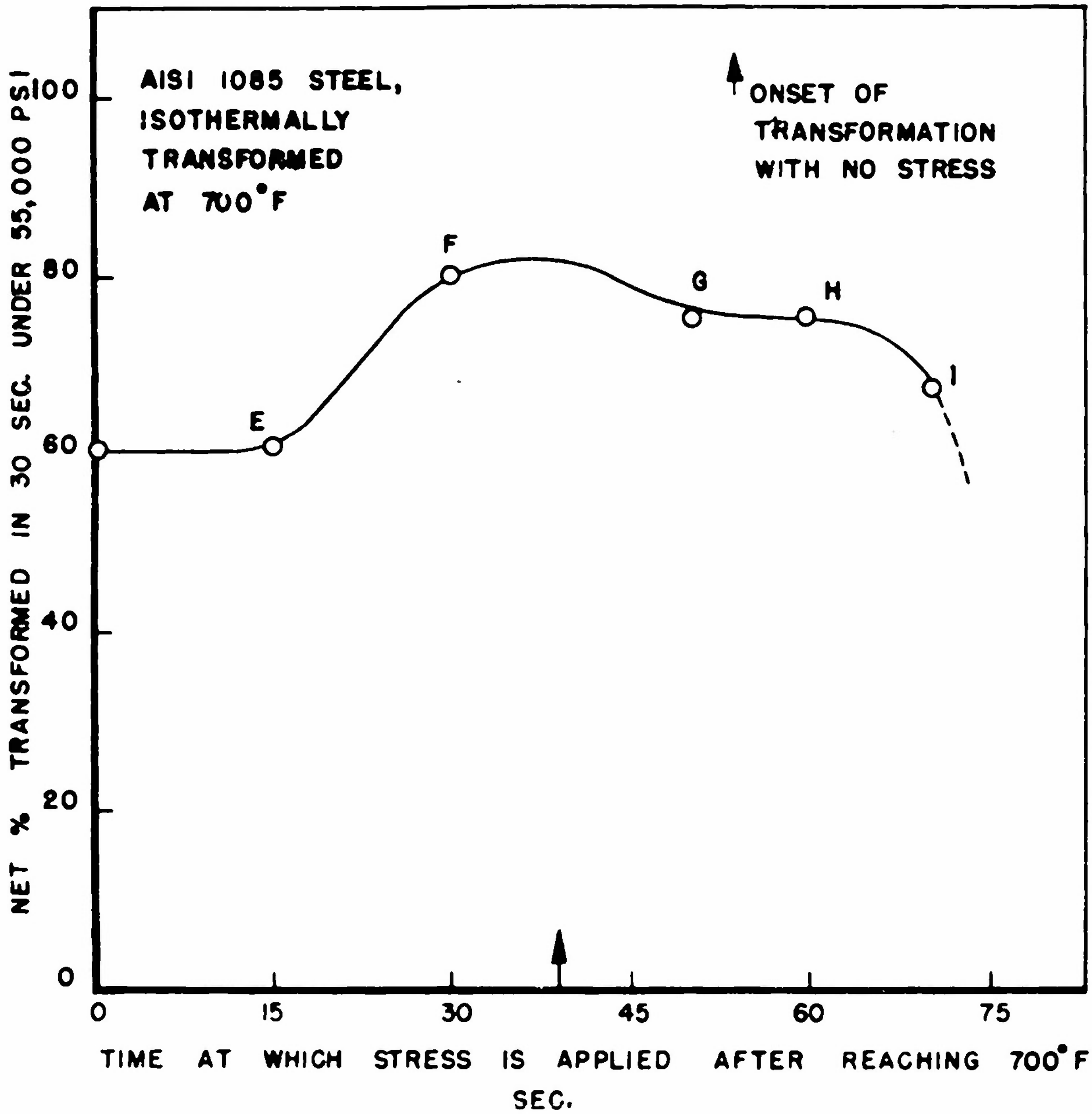


FIG. 10 NET % TRANSFORMED UNDER STRESS AS INFLUENCED BY THE TIME AT WHICH STRESS IS APPLIED AT THE TRANSFORMATION TEMPERATURE LEVEL

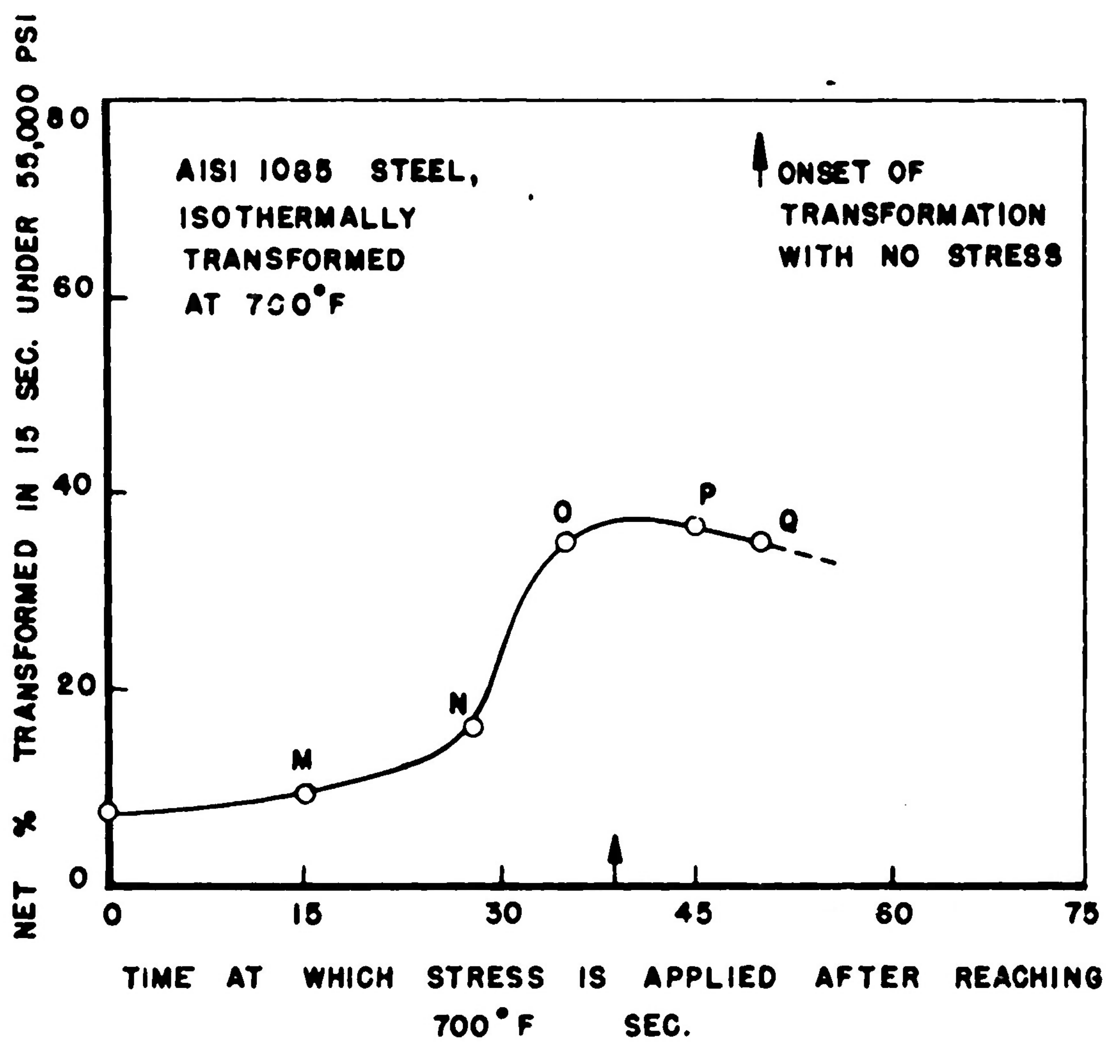


FIG.11 NET % TRANSFORMED UNDER STRESS AS INFLUENCED BY THE TIME AT WHICH STRESS IS APPLIED AT THE TRANSFORMATION TEMPERATURE LEVEL

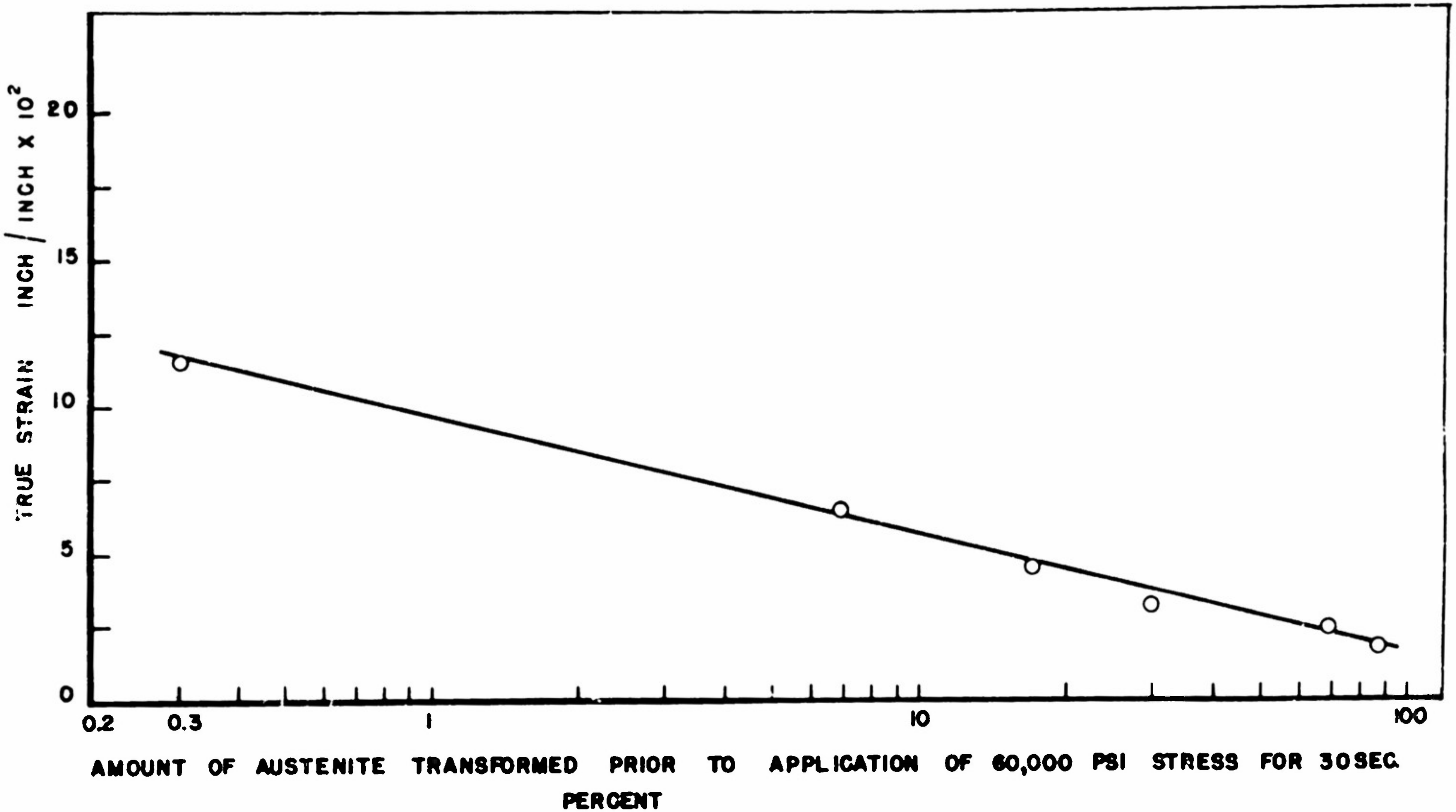


FIG. 12 VARIATION OF TRUE STRAIN WITH PERCENTAGE OF AUSTENITE TRANSFORMED AT COMMENCEMENT OF TEST OF AISI 1085 STEEL, ISOTHERMALLY TRANSFORMED AT 700° F

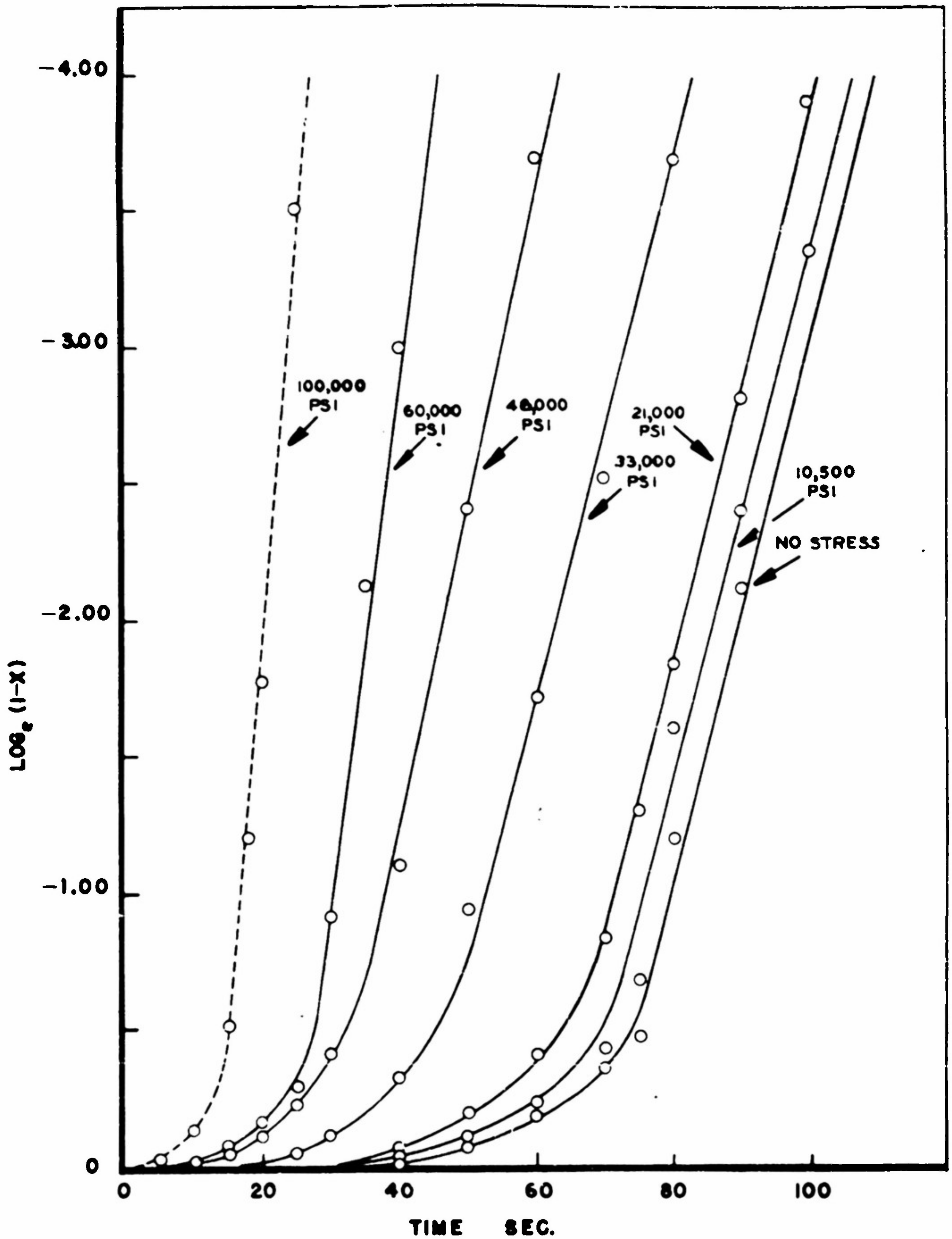
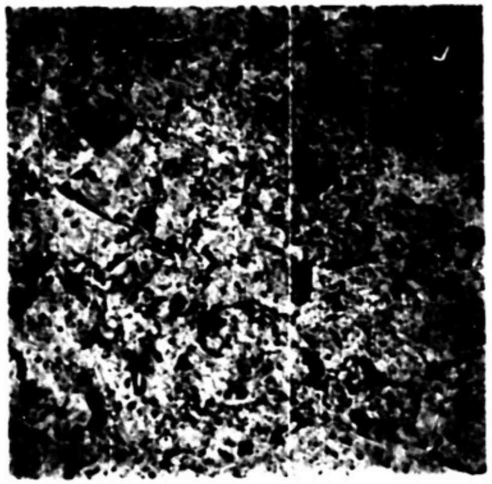
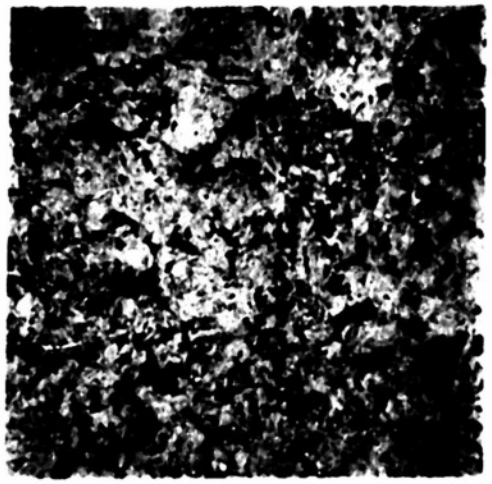


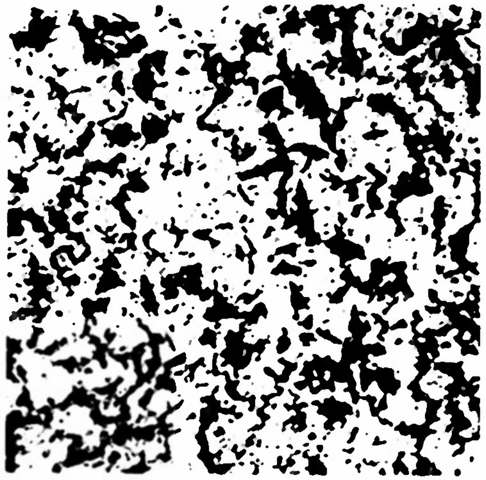
FIG. 13 RELATIONSHIP SHOWING THE VARIATION IN THE RATE OF DECOMPOSITION OF RESIDUAL AUSTENITE WITH APPLIED STRESS IN AISI 1085 STEEL, ISOTHERMALLY TRANSFORMED AT 700°F



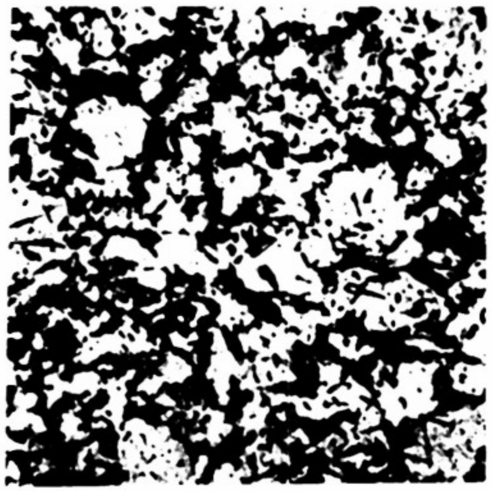
a. No stress; 45 sec.



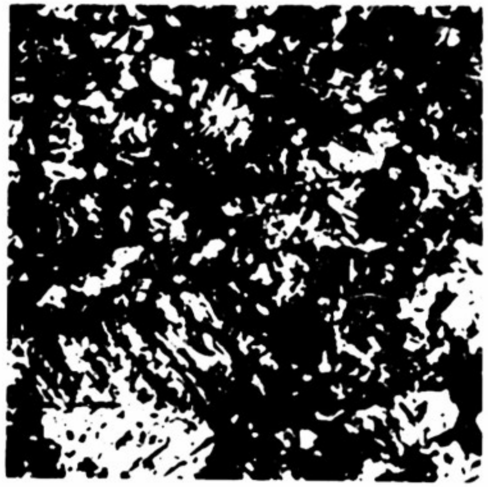
b. 10,500 p.s.i.; 40 sec.



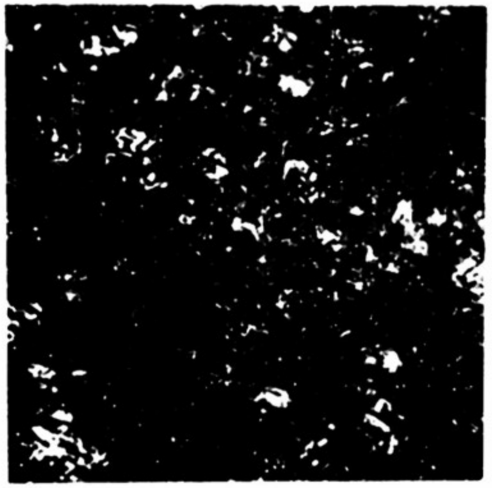
c. 21,000 p.s.i.; 45 sec.



d. 33,000 p.s.i.; 40 sec.

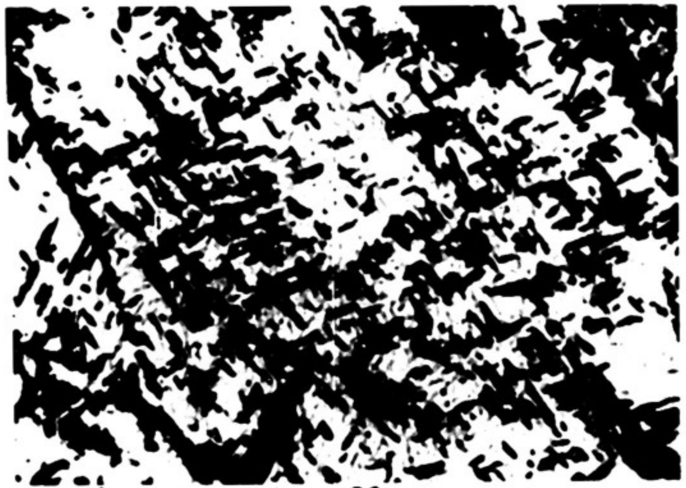


e. 46,000 p.s.i.; 40 sec.

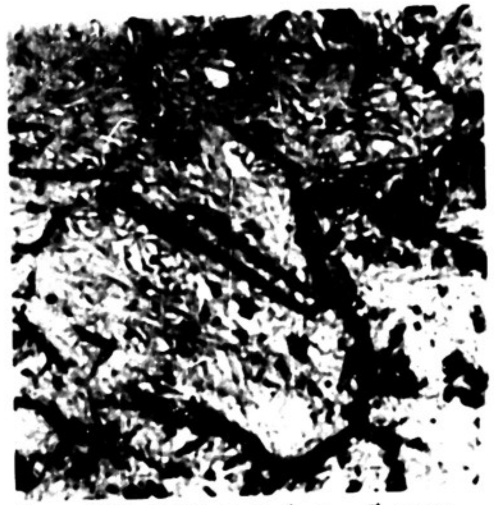


f. 60,000 p.s.i.; 40 sec.

Fig. 14 Illustrating the effect of stress on the amount of bainite isothermally formed at 700°F in AISI 1085 Steel 500 X
Etchant - Saturated Picral



a. 60,000 p.s.i.; 20 sec.



b. 100,000 p.s.i.; 5 sec.

Fig. 15 Illustrating preferred orientation of bainite (left) and twining of the prior austenite (now martensite) outlined by bainite (right). AISI 1085 steel transformed isothermally at 700°F
Etchant - Saturated Picral

1500 X

60,000 p.s.i.; 20 sec.

Fig. 16 Preferrential formation of bainites at grain boundaries in AISI 1085 steel transformed isothermally at 700°F
Etchant - Saturated Picral

500 X

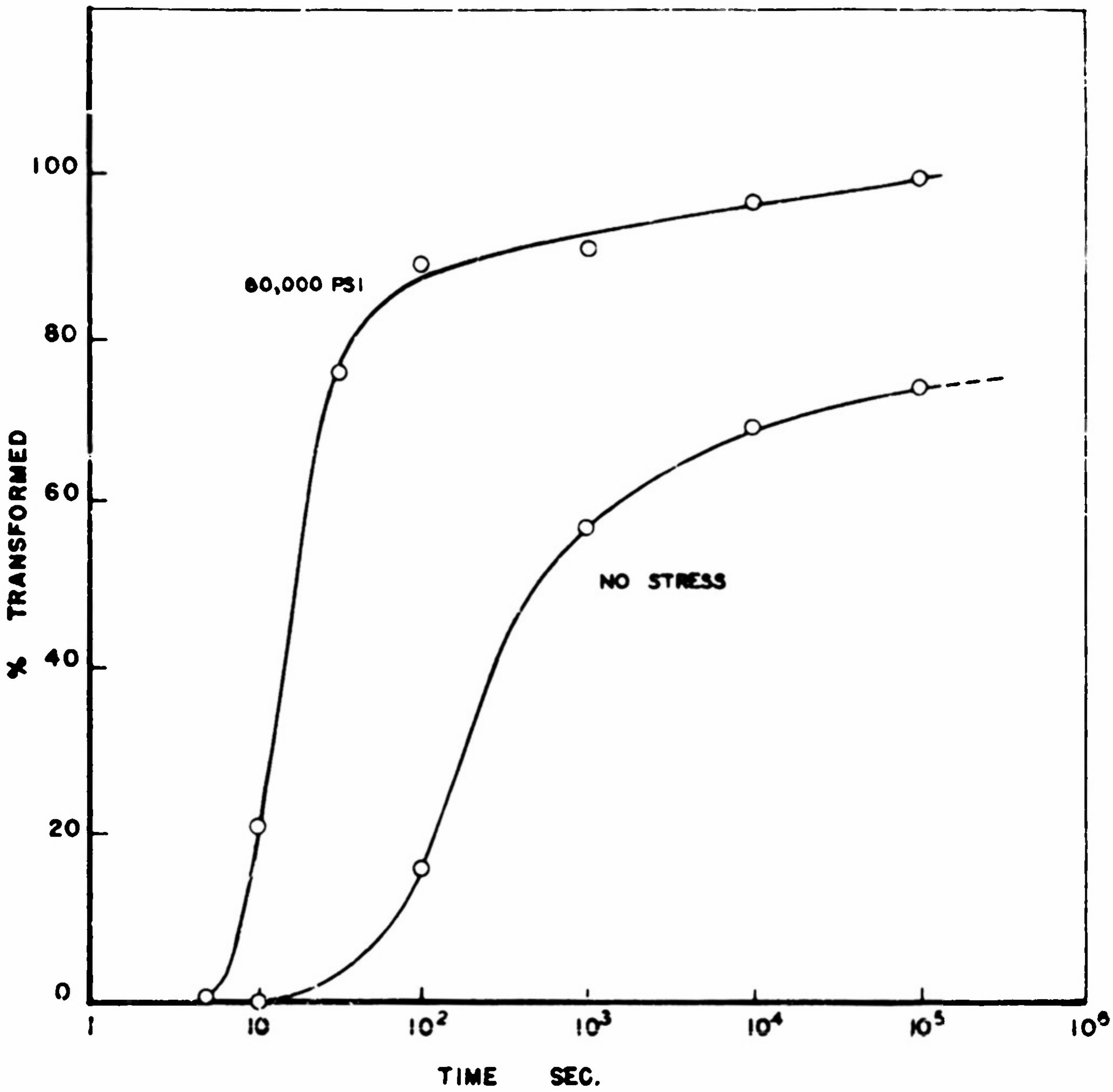
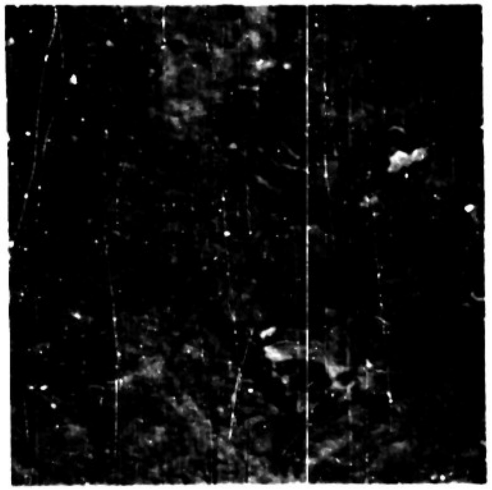


FIG. 17 AISI 4340 STEEL, ISOTHERMALLY TRANSFORMED AT 845° F



a. No stress; 100 sec.

b. 60,000 p.s.i.; 10 sec.

Fig. 18 Illustrating the effect of stress on bainite of AISI 4340 steel formed isothermally at 645°F
Etchant - Saturated Picral 1500 X